

TOP QUARK PRODUCTION DYNAMICS

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I discuss various aspects of the dynamics of top quark production both via the strong interaction (pair production) and via the charged current weak interaction (single top production).

1 The top quark and the Standard Model

The discovery of the top quark by the CDF and D0 collaborations at the Fermilab Tevatron in 1995¹ completed, (together with the discovery² of the τ -neutrino by the DONUT collaboration, also at Fermilab) the matter sector of the Standard Model. However, due its unique properties, the importance of the top quark discovery far exceeds completing a particle table. First, its large mass, close to the electroweak scale, indicates that it couples strongly to agents of electroweak symmetry breaking, making it an interesting probe of that phenomenon. Second, since its large mass implies a weak coupling to gluons, it is very suitable for perturbative QCD precision studies. Third, its large width ensures that properties such as its spin are not obscured by QCD hadronization, but can be studied directly. Together, these properties make precision study of the top quark and its quantum numbers, couplings to other particles possible. An accurate determination of these properties sets benchmarks for deviations from Standard Model physics. Because its mass is close to the EW breaking scale, observables involving the top quark are moreover likely to exhibit effects of new physics first.

The structure of the top quark interactions in the Standard Model is quite rich, cf. the color structure in the top-gluon interaction $g_s[T_a]^{ji}\bar{t}_j\gamma^\mu t_i A_\mu^i$, the chirality structure, parity violation and flavor mixing in the top- W coupling $(g/\sqrt{2})V_{tq}(\bar{t}_L\gamma^\mu q_L)W_\mu^+$, the parity violation in the top- Z coupling $(g/4\cos\theta_W)(\bar{t}[1-(8/3)\sin^2\theta_W]\gamma^\mu - \gamma^\mu\gamma^5)Z_\mu$ and the large strength but simple structure in the top-Higgs Yukawa interaction $y_t h \bar{t}t$. Precision studies of these interactions should take place via observables that have minimal theoretical uncertainty. This requires that their theoretical descriptions should, if possible, include quantum corrections, and that they allow implementation of experimental acceptance restrictions. This requires fully differential cross sections $d^{3n}\sigma/d^3p_1\dots d^3p_n$. Besides obviating the need to extrapolate into, or describe, regions of phase space where the theory is often less well-behaved, and thereby enabling better data-theory comparisons, such cross sections allow easy construction of different observables by selective integration over various kinematic variables.

For the foreseeable future top quarks will only be produced at hadron colliders, both via the strong and the weak interaction. The study of its production dynamics allows precision

measurements of the strength and structure of the couplings mentioned earlier, for verification or falsification.

2 Top pair production

The largest top quark production cross section involves their pair production via the strong interaction, and it is this process that led to the top discovery. A precise theoretical understanding of pair production dynamics is required to match the expected high experimental accuracy, to enable precise measurements of various Standard Model properties and serve as benchmark for new physics signals. At leading order (LO) this process occurs either via a $q\bar{q}$ or gg initial state. The former dominates ($\sim 85\%$) at the Tevatron, the latter ($\sim 90\%$) at the LHC. The NLO corrections are known both for the single-particle inclusive⁴ and fully differential case⁵. Beyond NLO resummations or approximations based thereupon are available. For the inclusive cross section the threshold-resummed form for the cross section is, schematically

$$\sigma_{q\bar{q}/gg} = \int_C \frac{dN}{2\pi i} \sigma_0 e^{wN} F_{q\bar{q}/gg}(N, \mu) \exp \left[\ln N g_1(\alpha_s \ln N, \mu) + g_{2,q\bar{q}/gg}(\alpha_s \ln N, \mu) + \dots \right] \quad (1)$$

with F representing the parton flux, and σ_0 a hard scattering function. The approach to threshold is described by $w \rightarrow 0$ (or, equivalently by $N \rightarrow \infty$, where N is the Mellin (or Laplace) variable conjugate to w) but its definition can vary. A minimal threshold is $w = s - 4m^2$. At fixed p_T one takes $s - 4(m^2 + p_T^2)$, while if one also fixes rapidity one may use $w = s + t + u - 2m^2$. The benefit of expression (1) is that it sums large $\ln N$ contributions, and that it reduces the factorization scale dependence of the hadronic cross section from $\mathcal{O}(\ln N)$ to $\mathcal{O}(1/N)$. Early resummations⁶ for this case varied in their choices and approximations for w , \int_C , and g_2 . The complete next-to-leading resummation⁷, requiring inclusion of coherent soft gluon emission⁸, based on a minimal choice of contour C , found that beyond NLO effects and residual scale dependence are small. See⁹ for recent numbers including uncertainties.

Alternatively one may construct a NNLO estimate¹⁰ by a two-loop expansion of the threshold-resummed form of the double-differential cross section¹¹, again schematically

$$\frac{d^2\sigma_{q\bar{q}/gg}}{dAdB} = \int_C \frac{dN}{2\pi i} h e^{wN} F_{q\bar{q}/gg}(N, \mu) \exp \left[\ln N g_1(\alpha_s \ln N, \mu) + g_{2,q\bar{q}/gg}(\alpha_s \ln N, A, B) + \dots \right] \quad (2)$$

where A, B represent kinematics variables: either t, u or $M_{t\bar{t}}, \cos \theta_{cm}$. The procedure is then to expand (2) to NNLO (judging the quality of approximation by comparing to exact NLO results) and a NNLO estimate after precise matching to NLO. This yields all terms of the form $\alpha_s^4 \ln^i w$, $i = 4, 3, 2$. Our Tevatron Run II estimate¹⁰ using CTEQ6M parton distributions¹² is

$$\sigma_{t\bar{t}}(1.96 \text{ TeV}) = 7.4 \pm 0.5 \pm 0.1 \text{ pb} \quad (3)$$

where the first and second error represent the kinematics and scale uncertainty, resp. While the inclusive cross section measures essentially the strength of the top quark QCD coupling, more differential cross sections could serve to explore the color structure in this coupling.

3 Single top production

The top quark may also be produced singly, without its anti-partner (and vice versa), via the charged current weak interaction. At lowest order, in a five-flavor scheme, one may distinguish production (s -channel) via off-shell W -bosons that are time-like (e.g. $u\bar{d} \rightarrow t\bar{b}$) or (t -channel) space-like (e.g. $ub \rightarrow td$). Associated production of a t with an on-shell W is negligible at the Tevatron, but contributes at the LHC. The study of single-top quark production dynamics

Table 1: NLO cross sections for single top production ($t + \bar{t}$) at the Tevatron and LHC for $m_t = 175$ GeV, per channel, and per machine. The indicated error in the third column is the scale uncertainty.

Channel	\sqrt{S}	$\sigma_{NLO}(\text{pb})$
t-channel	1.96 TeV $p\bar{p}$	1.98 ± 0.13
	14 TeV pp	247 ± 12
s-channel	1.96 TeV $p\bar{p}$	0.88 ± 0.09
	14 TeV pp	$10 \pm 0.9\%$

yields a direct measurement of the strength and the handedness of the top quark charged current coupling, it helps constrain the bottom-quark density, and leads to new benchmarks for new physics. The observation of this process at the 5σ level will require about 400pb^{-1} integrated luminosity at the Tevatron. The most promising strategy to observe this process was developed in Ref. ¹³, featuring in particular a veto on more than two jets in the central region to reduce the $t\bar{t}$ background. The s - and t -channels can be experimentally defined by the number of b tags on the central jets (2 and 1, resp.).

In most studies the single top production mechanism is approximated to be independent of its decay. The quality of this narrow-top-width approximation was investigated at leading order in Ref. ¹⁴ and found to work quite well.

Of foremost interest will be the direct measurement of the CKM matrix element V_{tb} . Of course, if one assumes the 3-family Standard Model, one need not bother: V_{tb} is constrained by unitarity to lie in the range $0.999 - 0.9993$. Without this assumption, the range is $0.08 - 0.9993$, so that a direct measurement of V_{tb} is very revealing. Since the production cross section is proportional to $|V_{tb}|^2$ this quantity can be inferred, using the branching fraction for $t \rightarrow Wb$ extracted from the pair production signal. Thus the eventual accuracy obtained for V_{tb} will depend on, among other things, the theoretical accuracy of the single-top production cross sections. The pair production cross section was discussed above. The fully differential NLO single-top production cross sections for Both s and t channel are given in Ref. ³. Both cut-off ^{15,16} and dipole subtraction methods ¹⁷ were used to handle intermediate infrared and collinear singularities, and found to give mutual agreement. Squared matrix elements as well as helicity amplitudes were computed to NLO, so that spin information is in principle available. Inclusive results, in agreement with earlier ones ^{18,13}, are given in table 1, for which CTEQ5M1 ¹⁹ parton distribution set was used. An example ³ of a more differential NLO observable is given in Fig. 1. Finally, I note that optimal bases for verifying the lefthandedness of the top's charged current coupling were identified in Ref. ²⁰. A LO analysis including backgrounds ¹³ gives good hope for a succesful measurement of this structure.

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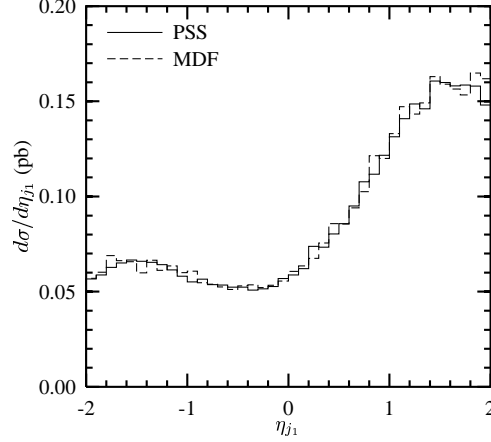


Figure 1: NLO pseudorapidity (η_{j1}) distribution of the highest p_T jet in t -channel single top production at the Tevatron with $\sqrt{S} = 2$ TeV. A k_T cluster algorithm ($\Delta R = 1$) was used, and jets must have $p_T > 20$ GeV and $|\eta| < 2$ to be accepted. Results using the cut-off (PSS) and subtraction methods (MDF) agree.

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